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Having laser intensities of 10^{21} W/cm^2 yield electrical field strengths of 10^{12} V/cm which is comparable to the field strength at the K-shell of neon. Instant field ionization becomes part of the laser-matter interaction allowing to transfer most of the photons momenta directly onto the ions by driving an electrostatic shock through the target equivalent to pressures of several 100 Gbar. Utilization of these high-pressure conditions in form of equation of state measurements, however, strongly depends on the contrast of the femtosecond laser pulse. Currently, the Livermore USP and JanUSP lasers reach contrast values up to 10^8. This is sufficient to explore near-isochorically heated materials at moderate intensities (10^{13}–10^{15} W/cm^2) attaining pressures around 100 Mbar.
[high-intensity short-pulse laser, high-pressure physics, relativistic plasmas, equation of state, Fourier domain interferometry]

1. Introduction

Characterizing the behavior of matter under high-pressure conditions, such as found in the interior of planets and stars, and, thus, acquiring the equation of state (EOS) data is of great interest to many different scientific communities, e.g., Geophysics, Astro-physics, Plasma physics, Solid-state [1-5]. Laboratory experiments that are focussing on generating pressures in excess of 1 Mbar depend, currently, on four major techniques: (i) The diamond-anvil cell method, which reaches static pressures of a few Mbar [6] and, thus, allows to study conditions comparable to those, that exist in the core of the Earth. (ii) Gas-gun driven shocks, which enable experimental high-pressure research in the 10-Mbar regime [7]. (iii) Laser ablation experiments using high-energy lasers, such as NOVA, have successfully extended EOS measurements to pressures of about 40 Mbar [8]. And (iv) short–pulse lasers which depend on the extremely fast (sub picosecond) energy deposition for generating high energy densities and, thus, high pressures in the target up to the 100 Gbar regime [9].

The ability to place moderate energies onto a target in less than 100 femtoseconds opens up the opportunity to examine matter at temperatures where ionization is significant but at densities that are at or near solid. Therefore, ultrashort-pulse lasers provide a tool to explore near-isochorically heated materials, especially, when used in combination with very thin targets. Simultaneous advances in short-pulse laser technologies and in experimental methods have pushed the focal laser intensities into the Zettawatt-per-square-centimeter regime (10^{21} W/cm^2) and, thus, are opening the window on the exploration of high-pressure physics in the 100 Gbar regime and beyond, i.e., conditions comparable to the solar core, for example.

The rapid energy deposition, even at moderate laser intensities (10^{13} – 10^{15} W/cm^2) generates high pressure shocks in targets. Attainable pressures are around 30 – 100 Mbar. At these pressures in compressed material, uncertainties in the EOS models arise from approximate theoretical treatments of many-particle interactions and modeled ionization for close-coupled, perturbing ions. Experiments are conducted to address some of the key uncertainties, including the ionization and temperature of strongly coupled plasma at known energy density [10] .

Extremely high intensities offer further opportunities. Particle-in-cell simulations predict that at an intensity of 10^{21} W/cm^2, the interaction of the light with a solid target can produce extremely large pressures. The radiation-induced pressure can exceed 300 Gbar [11]. This is a regime of highly nonequilibrium ion shocks from the direct transfer of the photon momentum of a high focal intensity laser.

Measurements are performed at the Livermore UltraShort Pulse (USP) laser facility [12]. High intensity experiments are performed at the companion JanUSP facility [13].

2. The Livermore USP facility – 100 Mbar EOS project

Femtosecond laser pulses with energies of only about 1mJ or less are being used to heat bulk and thin-foil targets. Applying a pump-probe technique, the expansion of the laser produced plasma and its complex dielectric properties are determined. Generally, these femtosecond laser produced plasmas have near solid densities, electron temperatures in the range from 10-100 eV, and pressures up to ten TPa, i.e., hundred Mbar. This strongly coupled plasma regime is highly challenging for theoretical predictions of the atomic state of the plasma. Significant differences in the average ion charge state and, thus, in the temperatures and pressures in currently implemented EOS models can be found. Such differences between the EOS models can only be resolved experimentally.

For our measurements, we use a pump laser pulse with a wavelength of 400 nm (2ω) and a pulse length of 120 fs (FWHM). The contrast ratio of the pump pulse is better than 10^7, i.e., comparing the peak intensity to the intensity values present at 1 ps before or after the peak. Measuring the pump pulse energy at the target surface, the energy of the specularly reflected light, the energy of the scattered fraction of the pump pulse, and the spatial intensity distribution of the laser spot at the target surface allows us to determine the amount of energy that has been deposited into the target. The expansion of the laser-produced plasma and its reflectivity are measured by means of Fourier-domain interferometry [14]. A 800 nm (1ω) probe pulse is split and temporally separated in a Michelson interferometer setup, such that they are reflected (under 45°) from the target before and after heating with the pump pulse occurs. The reflected light of the probe pulses is imaged onto a spectrometer slit. The spectrally dispersed pulses interfere and the interference pattern is recorded with a CCD camera. A sketch of the experimental setup is shown in Figure 1. The use of an independent probe allows one to decouple the diagnostic from the heating process and to obtain a time-resolved measurement of nearly-free expanding states. The result of such a "time series" of measurements is presented in Figure 2. These measurements were obtained using an aluminum bulk target, in particular, a silicon substrate with a 1-µm thick aluminum coating. The target composition was analyzed in detail using Rutherford. The analysis revealed that the target was composed of a (16±8) Å thick layer of hydrocarbons on top of a (26±3) Å thick layer of aluminumoxide followed by the pure aluminum layer. The aluminum bulk contained less than 0.06 atomic % of copper. The pump peak intensity was about 0.8×10^{14} W/cm^2. Both, the phase shift and reflectivity measurements were performed with a S-polarized probe pulse (electrical field vector of the probe pulse is parallel to the target surface) and a P-polarized probe pulse.

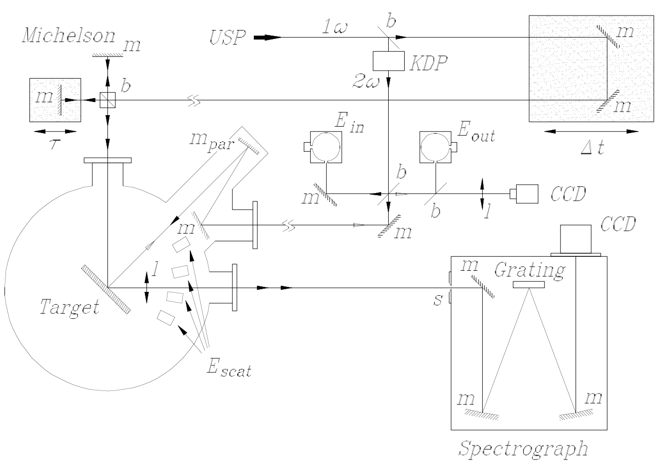

Fig.1 Sketch of the experimental setup, where *b* denotes beam splitters, *m* mirrors, *KDP* the frequency doubling crystal, and *s* the entrance slit of the spectrograph. Two translation stages in the probe beam path control the delay between the two probe pulses (♦) and the delay between the pump pulse and the second probe pulse (☟t). Integrating spheres are used to measure the relative energy of the incident pump pulse (E_{in}) and the normally reflected pump pulse (E_{out}). A set of photodiodes also monitors the amount of scattered pump pulse energy (E_{scat}). The interferograms are recorded with a *CCD* camera.

To interpret the experimental observations, the dynamic behavior of the hot expanded states is calculated using the hydrodynamic code LASNEX [15]. The phase and reflectivity are calculated by post-processing the hydrodynamic results using an electromagnetic wave solver, which treats the propagation of an electromagnetic wave in an inhomogeneous medium based on the Helmholtz equations. The basic hydro-calculations are made using a hybrid EOS table based on quotidian equation of state (QEOS) and the many-body active expansion method (ACTEX) [16,17]. A dense plasma conductivity model was also implemented [18]. Both of these material models have found reasonable success in modeling femtosecond laser matter interactions [19,10]. The expanded states are treated as a two-temperature fluid. In all the hydrodynamical calculations presented here, the absorbed pump energy was constrained to match that observed experimentally. The result of the simulations is given in Figure 2.

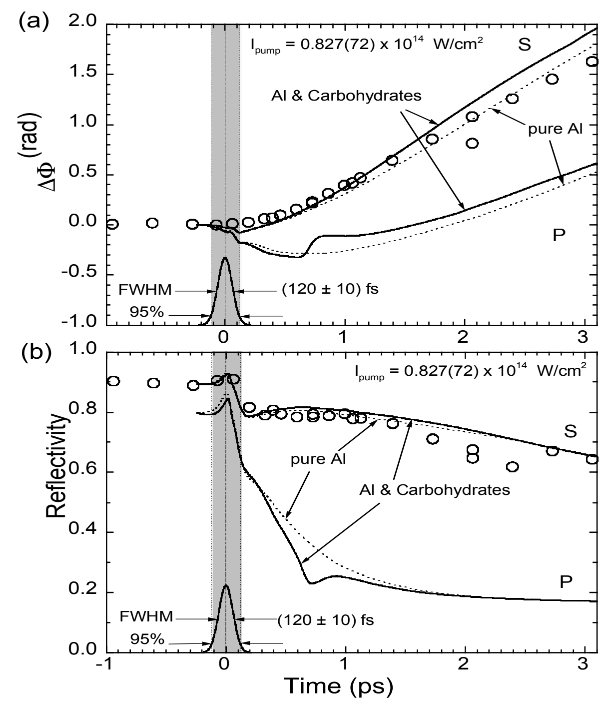

Fig.2 (a) Phase dynamics and (b) reflectivity for the S- and the P-polarized probe pulses. The symbols O and ☞ denote the experimental data. The calculations which take into account two different targets – pure aluminum and aluminum with a 3Å thick layer of hydrocarbons – are based on the ACTEX-QEOS hybrid table. Note, that the calculations for the target with the layer of hydrocarbons qualitatively reproduce the extremely fast temporal feature in the phase shift dynamics at t ≈ 0.7 ps. The steep drop in the reflectivity of the P-polarized probe, too, is mimicked better when implementing this thin layer.

The difference between the two calculations (dotted and solid lines in Figure 2) is a result of applying different target compositions. The dotted lines represent the simulations for a pure aluminum target. The solid lines, however, represent a target composition using the information gained with the Rutherford backscattering analysis. Although the modification of the target is only a very thin layer (only about 3Å thick) of Hydrocarbons it seems to have a dramatic impact on the qualitative behavior of the phase shift and reflectivity of the P-polarized probe. This surface layer phenomenon can be understood by examining the hydrodynamic and resonance absorption behavior of the P-polarized probe which early in time shows a highly localized resonance absoprtion. In fact, the little step in the P-polarized phase shift just about 0.7 ps after the heating pulse can be attributed to the transition of the resonance absorption peak from the hydrocarbon plasma into the aluminum bulk plasma.

3. The Livermore JanUSP facility – 100 Gbar ion shock heating

As seen in Figure 3, the JanUSP has the typical features of a regular Ti:sapphire UltraShort Pulse laser facility: pulse duration about 100 fs, 1-ω wavelength 800 nm. The final amplification stage, however, contains the world's largest Ti:sapphire crystal (10 cm diameter) which is pumped by one arm of the Janus laser, which generates a 130 J, 6ns laser pulse at 532nm. Initial measurements of the focal intensity of the JanUSP laser included the characterization of the temporal and spectral profile using frequency-resolved optical gating and imaging of the spatial intensity profile. Having a pulse duration of 80 fs (FWHM), a focal spot size of only 2.0 x 1.6 μm^2, and a total laser pulse energy of 15 J yield a focal peak intensity of 2×10^{21} W/cm^2 at 800 nm.

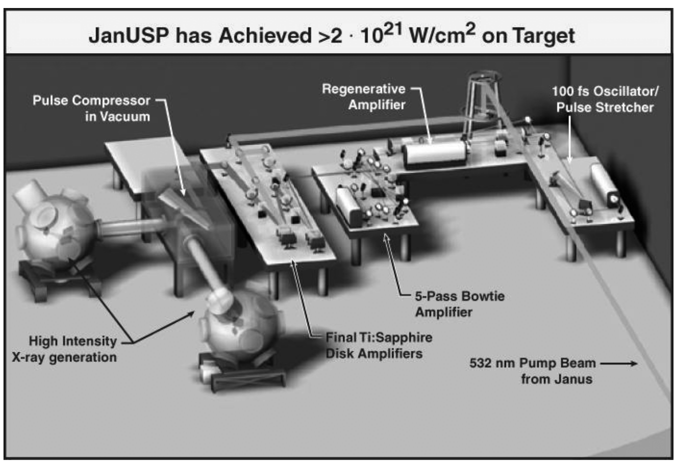

Fig. 3 Schematic of the JanUSP laser facility setup. The Janus laser is located in an adjacent laboratory.

At such high intensities the electrical field strength in the focal region is around 10^{12} V/cm which is comparable with the electrical field strength at the K-shell of neon. Thus, instant field ionization of the ground state electrons becomes part of the laser-matter interaction. Thus, the laser pulse drives an electrostatic shock through the target. The range of ions in a solid density target, however, is very short. Therfore, the ions "loose" their energy within a very small volume creating energy densities in the order of several GJ/cm^3 (10 GJ/cm^3 = 10^{16}J/m^3 = 10^{16} Pa = 100 Gbar). This ion shock heating mechanism would be the method of choice for the production of plasmas with kilovolt opacities. The high electric field strength of the laser also immediately accelerates the electrons into a relativistic regime. The electron quiver energy at an irradiance of $I\lambda^2 = 10^{21}$ W cm^{-2} μm^2 is approximately 10 MeV, and the Bremsstrahlungs spectrum is dominated by high-energy γ's. The flux and spectral distribution of γ radiation produced by such means has already been observed and measured at the Petawatt laser [20]. Initial measurements verifying the presence of photonuclear activated gold - after the gold target had been "exposed" to the 10^{21} W/cm^2 laser intensity - have been performed at JanUSP, as well [21].

Besides the high electric laser field there is, of course, also a high magnetic flux density in the laser's focal region. In particular, 10^{21} W/cm^2 translate to about 3×10^5 Tesla which is comparable to the magnetic fields at the surface of white dwarfs.

4. Summary and Outlook

The measurements of the expansion and optical properties of the plasma using a pump-probe setup and Fourier-Domain Interferometry have reached a precision where it can be used for experimental guidance of the development of EOS models in this high-pressure, strongly-coupled plasma regime. The results suggest that the S-polarized phase shift is a sensitive test of equation of state. The P-polarized phase change and reflectivity measurements appear to provide a spatially localized diagnostic of the dynamical behavior of a surface layer. The different response of the probe pulses regarding the surface composition clearly shows the different topology of the resonance absorption of the S- and the P-polarized probe pulses.

Initial experiments performed on the JanUSP laser confirmed that focal intensities of $>2 \times 10^{21}$ W/cm^2 have been achieved, which represents an uncharted regime in laser-plasma interaction and high-pressure physics. Utilization of these extreme parameter space with respect to precise equation of state measurements, however, requires a very high laser pulse contrast. The goal is to achieve a contrast of 10^{12} to ensure that the initial conditions of the target are not dictated by laser prepulse phenomena.

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